Results of Outdoor to Indoor Propagation Measurements from 5-32GH

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The demand for wireless services has increased exponentially in the last few years and shows no signs of slowing in the near future. In order for the next generation wireless to provide seamless access, whether the user is indoors or out, a thorough understanding and validation of models describing the impact of building entry loss (BEL) is required. This information is currently lacking and presents a challenge for most system designers. For this reason empirical data is needed to assess the impact of BEL at frequencies that are being explored for future mobile broadband Applications. This paper present the results of measurements of outdoor-to-indoor propagation from 5-32 GHz in three different buildings. The first is a newer building that is similar in construction to modern residential home. The second is an older commercial office building. The last building is a very new commercial office building built using modern "green" building techniques. These three buildings allow for the measurement of propagation losses through both modern and older materials; such as glass/windows and exterior block and siding. Initial results found that at particular spatial locations the BEL could be less than 1dB or more than 70dB with free space losses discounted (this is likely influenced by multipath). Additionally, it was observed that the PDF distributions of a majority of the measurements trended toward log-normal with means and standard deviations ranging from 8-38dB and 6-14dB, respectively.

I. Introduction

This contribution presents measurements of outdoor-to-indoor propagation from 5-32 GHz. For this contribution two different buildings were measured. The first is a newer building (built in 2009) that is similar in construction to a modern residential home in the United States. The second is an older commercial office building (built in 1945). The last building is a very new commercial office building built using modern "green" building techniques. These three buildings allow for the measurement of propagation losses through both modern and older materials; such as glass/windows and exterior block and siding. The excess loss (with free space losses removed) for all of the buildings is presented in the document.

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II. Experimental Setup

The signals used during this experiment were continuous wave (CW) at 5, 12, 25.5 and 32 GHz. The antennas used for both the transmitter and receiver were identical dual ridge horn antennas (MVG Model Number: SH4000) with the following characteristics:

Figure 1: Picture of the antenna used for the experiment

Table 1: Transmit and Receive Antenna Parameters

Antenna Gain	4.5-13 dBi
Beamwidth	40°
Gain Stability	±1 dB

The outdoor transmitter consisted of a signal generator (Anritsu MG3690C) connected to the dual ridge horn antenna, with an optional amplifier that was not used for this experiment but could be included for future measurements if necessitated by the expected free space loss. The receiver consisted of an identical antenna connected to a spectrum analyzer (Agilent E4446A). Initially two identical receivers were setup with the intent on simultaneously measuring the outdoor reference and the indoor locations, as indicated by ITU-R P.2040-1. However due to observed coupling between the two receive antennas, it was decided that the outdoor and indoor measurements would be conducted separately.

III. Building Descriptions

The first building that was measured is a recently constructed building similar to a modern US residential building. The building’s exterior is made up of vinyl siding followed by plywood sheeting with metal studs with fiberglass insulation in-between covered by final layer of drywall. The windows in the building are standard double pane low-emissivity windows used in most modern US construction.

The second building is an older commercial office building. The exterior walls are composed of 10.2 cm of brick on top of 20.3 cm of concrete block followed by 2.5 cm furring strips and 1.9 cm layer of plaster. The windows are older and made of double pane glazed glass with aluminum frames.

The third building is a new building that was constructed with a focus on environmental factors, e.g. a lot of recycled/energy efficient material and low E glass windows. There also is a reflective thermal coating on the windows to help keep the building cool in the summer and warm in the winter. This coating as well as the low E glass seems to have a large effect on the transmission of signals into/out of the building, as will be shown in the results that follow.

Figure 2: Photograph of the front of Building 1 (left) and Building 2 (right) and Building 3 (bottom)

Testing Locations

For each test point the transmitter was positioned so that the signal had normal incidence onto the face of the building. The receiver was then positioned in direct line of sight (LOS) at 0° azimuth with reference to the transmitter. The height of the transmitter and receiver were matched to eliminate any changes in the received signal level due gain deviations in the antenna patterns. Figure 3 shows the locations of each antenna during the experiment for both the reference measurement and the actual building measurement.

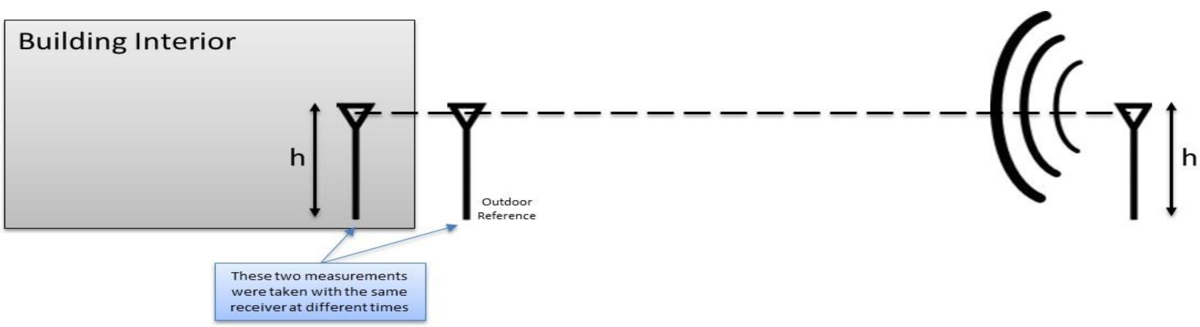

Figure 3: Depiction of Experimental Setup

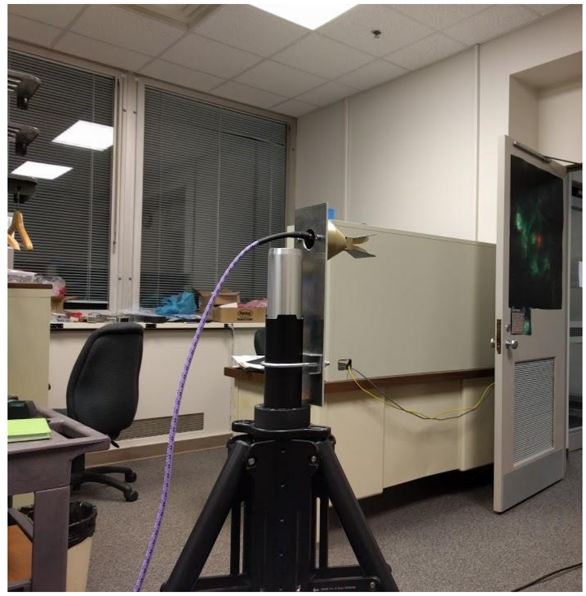

Figure 2: Photos of the transmitter and receiver during testing

After the outdoor reference measurement was taken, the receiver was moved into the building and positioned to again be a at 0° azimuth with reference to the transmitter and at the same height as both the outdoor measurement and the transmitter. A laser transit system was used to match the heights and to account for any changes in ground elevation. For each transmitter location the indoor measurements were stepped linearly, moving farther away from the transmitter at each test point taking care to ensure that the 0° azimuth with reference to the transmitter was maintained thought the experiment.

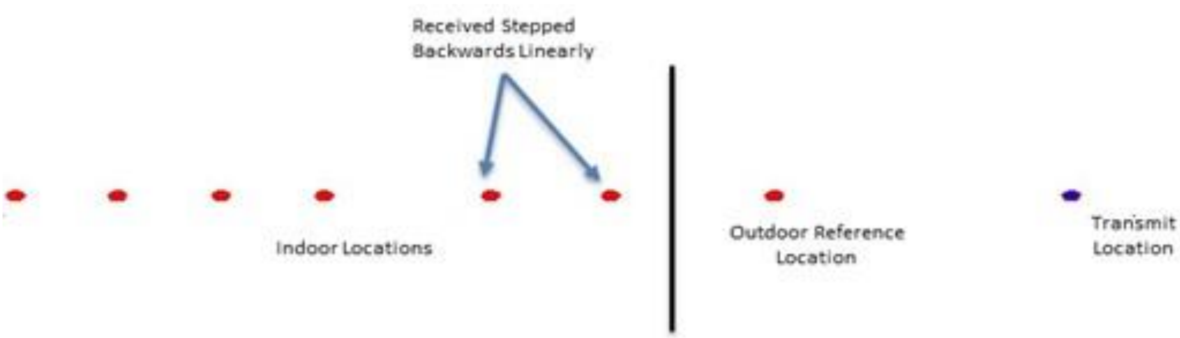

Figure 3: Diagram showing how receiver was linearly stepped into building

When the rear of the building was reached the transmitter was repositioned to the next location and the process was repeated. The transmitter was stepped across the face of the building to ensure that there was always normal incidence on the building face and so that the transmitter and receiver were always pointed boresight to reduce/eliminate signal level changes due to gain variations over the beamwidth. The floor plans and the testing locations of each building are shown in Figures 6-8.

The spatial density of points needs to be considered when conducting an experiment such as this. The testing locations were chosen to be somewhat uniformly distributed and to ensure that all of the unique aspects of the building were sampled (e.g. windows, doors, large wall sections, hallways, etc). For Building 1 the spatial density was 1 point per 5 square meters, for Building 2 it was 1 point per 14 square meters and for Building 3 it was 1 point per 27 square meters. The points were designated by defining an arbitrary origin at a location inside the building, then referencing all spatial locations to that origin.

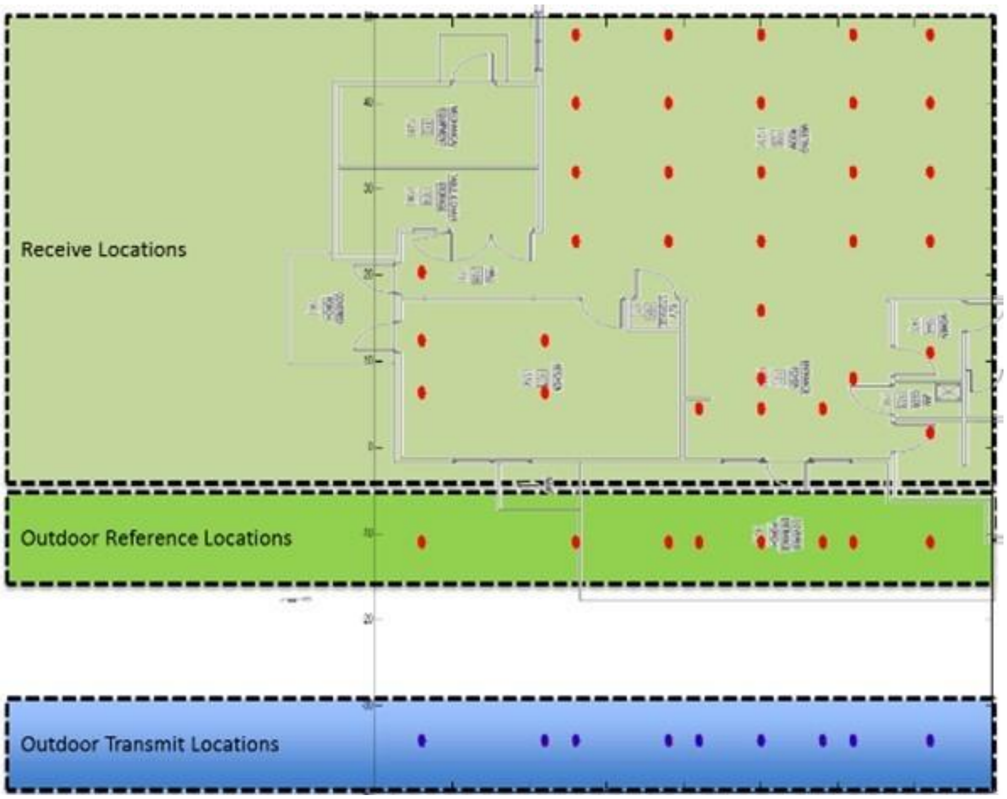

Figure 4: Floor plan and testing locations for Building 1

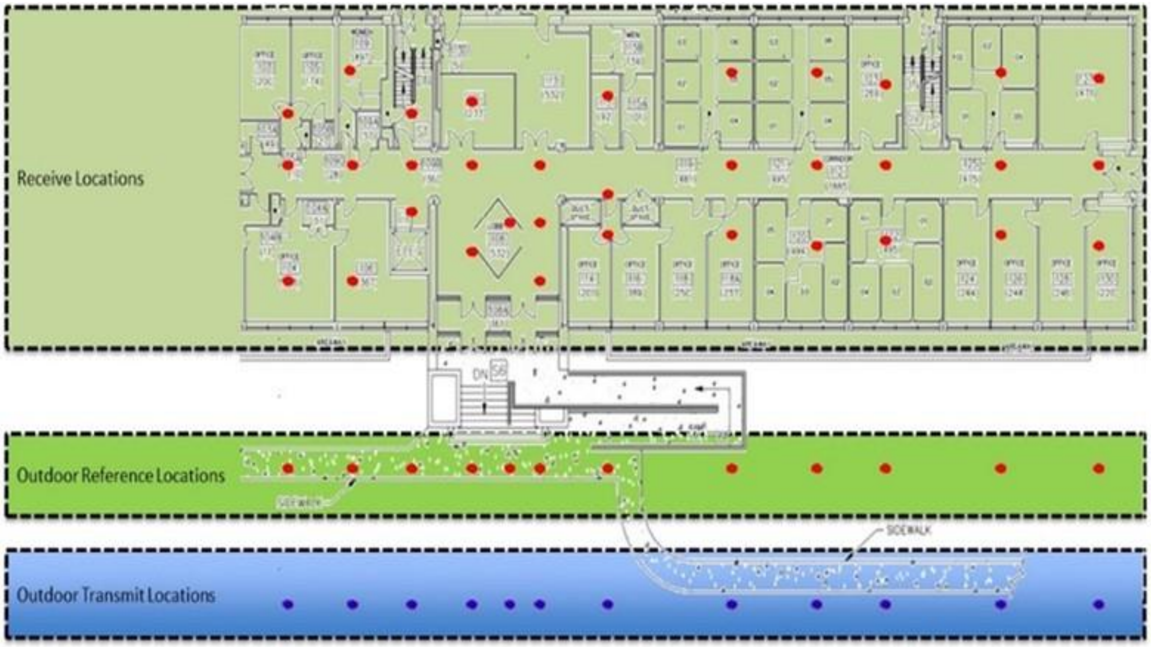

Figure 5: Floor plan and testing locations for Building 2

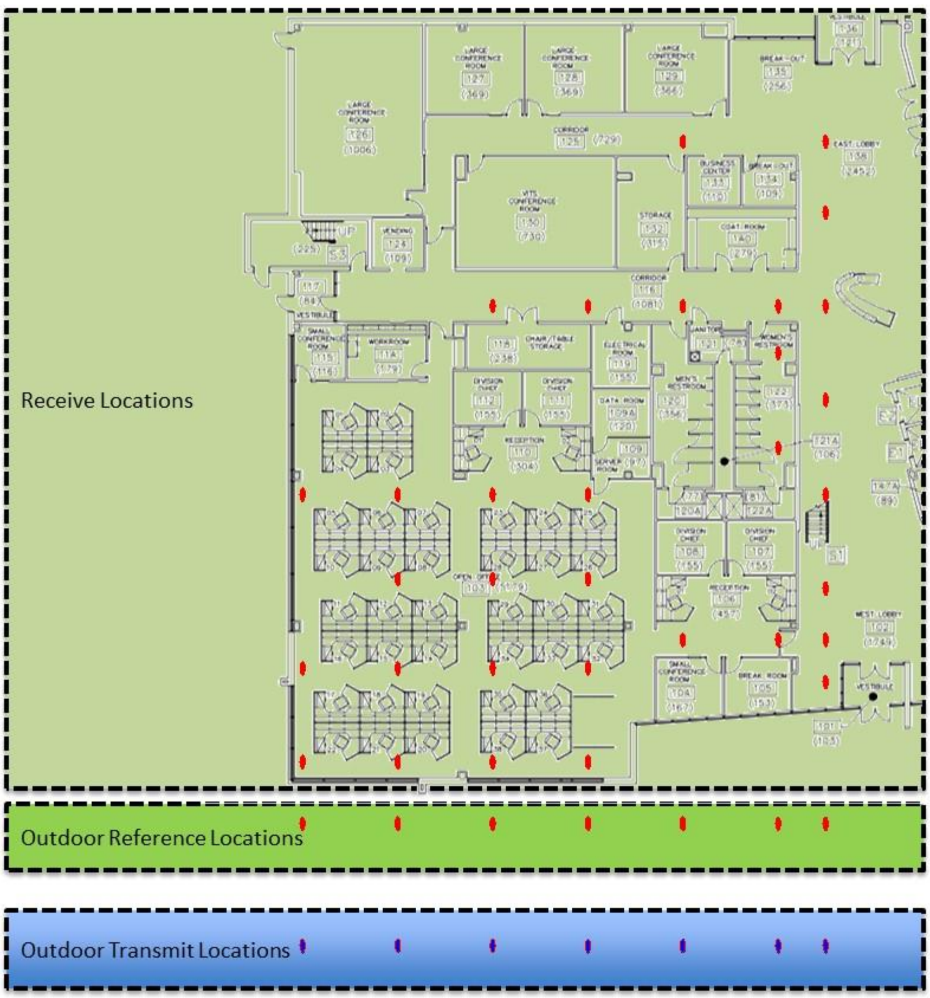

Figure 8: Floor plan and testing locations for Building 3

IV. Data Processing

At each test point in the experiment a minimum of two minutes of data per frequency was collected at 1 Hz. In post processing the temporal data at each test point was subjected to a trimmed average by calculating the standard deviation (σ) of all the samples at a particular point and frequency then removing any outliers (defined as values exceeding ±3σ) then averaging the remaining points. The total number of outliers removed from the data set comprised less than 0.5% of the total samples collected.

The building entry loss in this paper is defined as:

$$BEL = P_{ref} - P_{indoor} - L_{FS}$$

Where BEL is the building entry loss, P_ref is the power received at the outdoor reference location, P_indoor is the received power at the indoor location and L_FS is the additional free space loss that occurred from the signal traveling past the reference point and into the building.

V. Measurmet Results

The following sections contain the results of the measured building loss from each building. The results are analyzed and presented in tabulated form and in the form of PDF distrobutions.

A. Tabulated Results

The tabulated measurements results are presented in Tables 2-4. From the data in Tables 2-4, it can be seen that the range of building loss seen is quite large depending on the position inside the building. The minimum BEL seen was on the order of 1-2dB with the maximum in excess of 50dB. It is important to note that for each building the measurements were taken over the course of a single evening and that during the time measurements were taken the temperatures deviation was less than 6°C. Additionally, there was no precipitation during testing.

TABLE 2: Tabulated Building Loss Results for Building 1

Frequency [GHz]	Minimum [dB]	Mean [dB]	Maximum [dB]	Standard Deviation [dB]
5	1	8.5	27	6.5
12	.5	9.5	23.5	5.5
25.5	3.5	14	32	6
32	2.5	17	40	7.5

TABLE 3: Tabulated Building Loss Results for Building 2

Frequency [GHz]	Minimum [dB]	Mean [dB]	Maximum [dB]	Standard Deviation [dB]
5	1	13.5	32.5	9.5
12	1	14	30	9.5
25.5	1.5	17.5	52.5	15
32	2.5	14.5	45	14.5

TABLE 4: Tabulated Building Loss Results for Building 3

Frequency [GHz]	Minimum [dB]	Mean [dB]	Maximum [dB]	Standard Deviation [dB]
5	11.5	29	53	12
12	16	31	51.5	11
25.5	13	35.5	69	14.5
32	20.5	38	58.5	12

It is important to note that all of the buildings presented a multipath rich environment. This created a substantial amount of variation in the received signal as a function of position. Multipath has the potential to be both constructive and destructive. When considering any single spatial point, the contribution of multipath should be taken into account, and therefore some of the minimum (and maximum) values in the above tables are likely influenced by multipath.

From these plots it appears that the measurement results are more uniform in Building 1. This is due to the open nature of the building, as seen from the floor plan. Once inside building one the majority of the area is contained inside one large “great room” with very few interior walls or furniture. Conversely, Building 2 and 3 are subdivided into many offices and those offices are further divided into individual cubicles each containing standard office furniture, desk, chairs, bookshelves, etc.

In all of the buildings there appeared to be a large amount of multipath as the signal diffracted/reflected off the building interior. For the purpose of this experiment the receivers were kept pointed boresight with the transmitter but a large amount of signal variation occurred with azimuth rotation. This effect needs to be explored further to characterize the overall role of multipath in building entry loss.

B. PDF Distrobutions

Next the probability density functions (PDFs) of the data sets are considered. The distributions appear to be lognormal with the mean and standard deviation varying with frequency. Plotted alongside the actual PDF results are simulated lognormal PDFs using the means and standard deviations listed in Tables 2-4. The results from Building 1 more closely match the simulated log normal PDFs, this is most likely due to the open nature of the building with very few interior walls or furnishings. Additional data points for Building 2 and 3 could potentially enhance the PDF results and give a more accurate indication as to the PDF distributions.

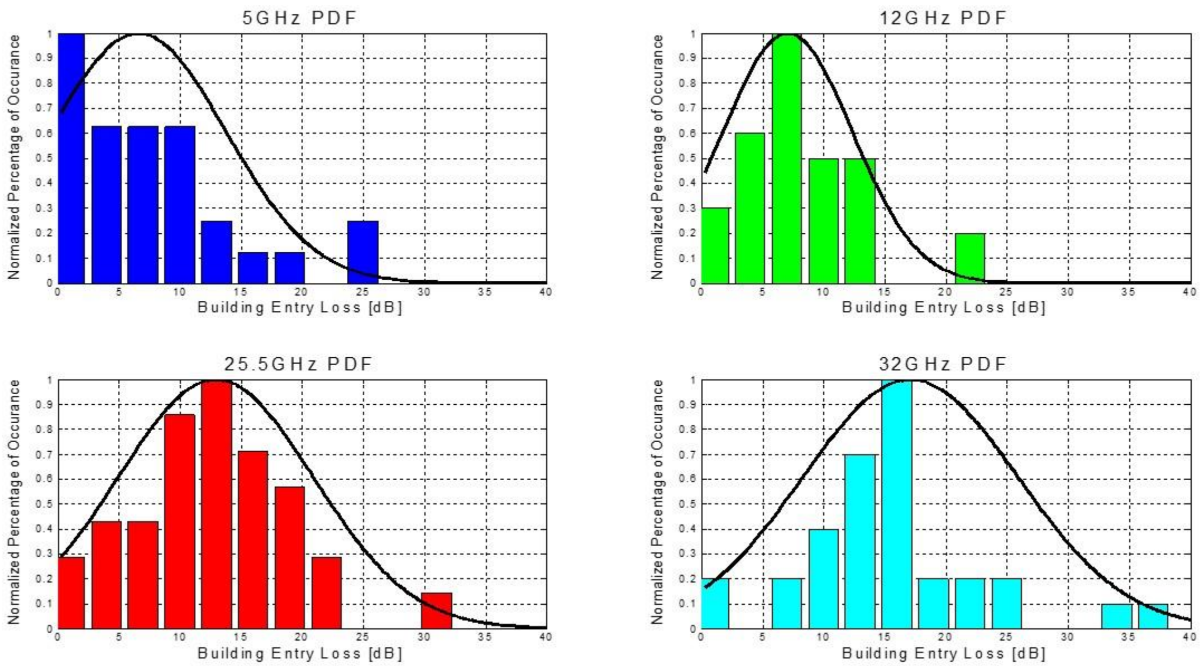

Figure 9: PDF Distributions of Building 1

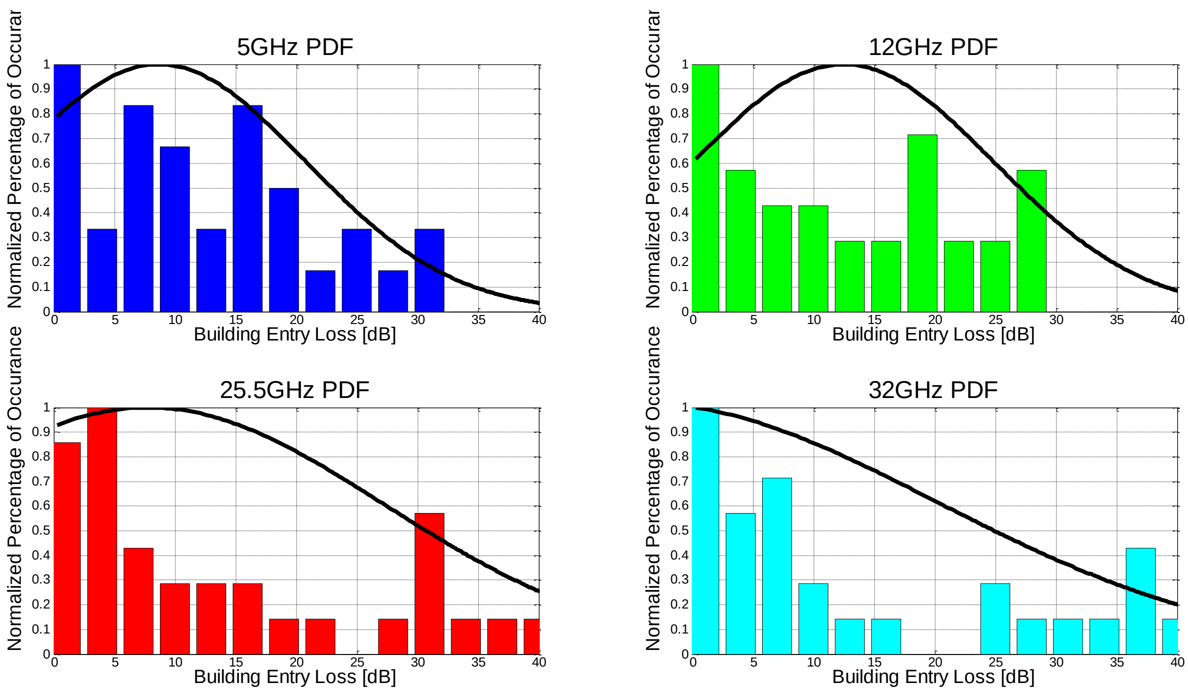

Figure 10: PDF distributions of Building 2

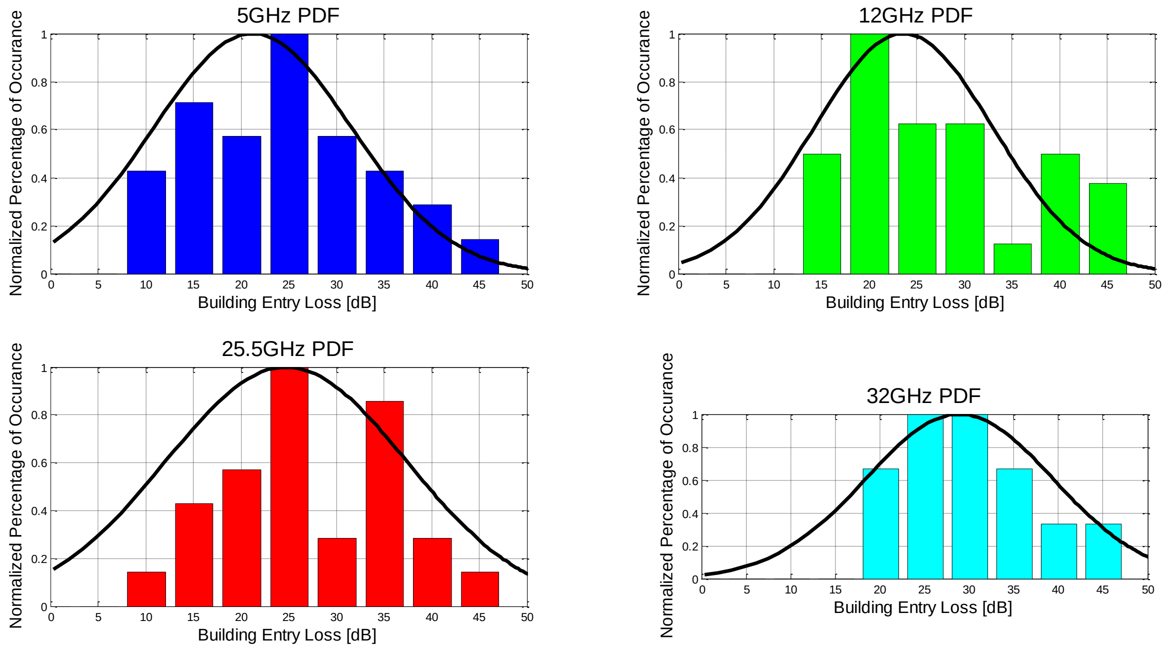

Figure 11: PDF distributions of Building 3

More buildings will need to be measured in order to expand upon and examine these trends in more depth and confirm the conclusions about the distributions; but this information is promising for future modeling purposes.

VI. Conclusion

The characterization of building entry loss is not a trivial task to undertake. There are many variables which must be isolated, such as free space loss, multipath, RF clutter etc. This experiment sought to eliminate as many variables as possible and focus only of the actual loss introduced by the building itself. The results of this study have shown that building entry loss is dependent upon the building which is being studied both in terms of its composition and its contents (interior walls, furniture, etc.). Within the three buildings studied, building entry loss as low as 0.5 dB and in excess of 50 dB was observed. However, even though the building results varied some of the PDF distributions appear to be lognormal, these results will be expanded upon and examined in more depth when additional buildings are completed.

References

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